Final Report for DOE Advanced Detector Award de-fg02-07eR-41491

“Development of a 10 picosecond time-of-flight Counter”

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Executive Summary:

This Advanced Detector Research proposal presented a plan to develop an extremely fast time-of-flight detector for measuring the arrival time of beam protons scattered at small angles in high energy hadron colliders, such as the Large Hadron Collider (LHC). The proposed detectors employ a gas or quartz Cerenkov radiator which produce light when a proton passes through them, coupled to a micro-channel plate photomultiplier tube (MCP-PMT) that converts the light to an electrical pulse. The very small jitter of the pulse time provided by the MCP-PMT, combined with downstream electronics that accurately measure the pulse time results in a time-of-flight measurement of unprecedented accuracy. This ADR proposal was extremely successful, culminating in the development of a 10 ps resolution time-of-flight system, about an order of magnitude better than any time-of-flight system previously deployed at a collider experiment.

The primary areas of advance were the usage of new radiator geometries providing fast detector signals, using multiple measurements to obtain a superior system resolution, and development of an electronics readout system tuned to maintain the excellent timing afforded by the detector. Test beam and laser tests have improved the knowledge of MCP-PMT's and enabled the evaluation of the new detector concepts. In addition to being a generally useful detector concept, these fast timing detectors are a major component of proposed upgrades to the LHC ATLAS and CMS detectors, and if deployed could significantly enhance the discovery potential of these detectors, including contributions to the measurement of the properties of the Higgs Boson. In addition to the potential for furthering fundamental understanding of nature, the knowledge gained on MCP-PMT's could be useful in developing improved versions of these devices which have promise in diverse fields such as biological and medical imaging.

Comparison of Goals and Objectives of Project with Accomplishments:

Primary Goal: We proposed to develop an order of 10 ps time-of-flight detector for measuring the arrival time of beam particles in fixed target experiments or particles scattered at small angles in high energy hadron colliders.

Accomplishment: With the gas Cerenkov detector we obtained a measurement of 13 ps in test beam (from the detector/PMT combination). Since then a 10 ps measurement using cosmic rays and a faster PMT from Photek has led to a 10 ps measurement. We obtained a measurement of 40 ps for one bar of a quartz Cerenkov detector (including the readout electronics) and demonstrated that the measurement improves with the square root of the number of channels per detector (as expected), implying that two eight-channel detectors would provide a 10 ps measurement.

Objective: Evaluate and improve the detectors with the use of test beam.

Accomplishment: We had four test beams (Fermilab March and August 2007, CERN October 2007 and July 2008) resulting in a major improvement in detector design (using long quartz bars instead of short quartz bars) and performance.

Objective: Develop and test electronics capable of 10 ps measurement, including constant fraction discriminator (CFD) and time-to-digital converter (TDC).

Accomplishment: We tested the Louvain CFD in test beam and showed that it is compatible with our detector needs, and further demonstrated with the UTA laser that it has about 5 ps resolution for the 10 photoelectrons expected for our detector. Our Alberta colleagues built a TDC board incorporating the CERN HPTDC chip, which is suitable for our readout. In UTA laser tests we established that this TDC has about 14 ps resolution which is good enough not to degrade our single bar resolution of 40 ps.

Objective: Identify each component of the resolution to allow focus on the component that is the largest contributor to the resolution.

Accomplishment: Using the oscilloscope and laser purchased with project funds, we were able to isolate the resolution contribution from the detector, MCP-PMT, and electronics. The electronics are fine for the quartz detector, a commercial solution can be applied for the gas detector (which only has one channel per detector and can thus a more expensive solution can be used). Initially the largest contributor to the resolution was the CFD; after developing and testing the new Louvain CFD, the MCP-PMT became the largest contribution. Improved MCP-PMT's (smaller microchannel or pore size) reduced the PMT resolution putting it on the same scale as the quartz detector detector. For the gas detector the improved MCP-PMT reduced the overall time resolution, and is still the limiting factor.

Project Summary

Overview. The main goal of the DOE ADR “Development of a 10 picosecond time-of-flight Counter” was to develop an order of 10 ps time-of-flight detector for measuring the arrival time of beam particles in fixed target experiments or particles scattered at small angles in high energy hadron colliders. The major budgetary items were a fast oscilloscope and a pulsed laser system. The work plan included using simulations to develop the detector concepts and test beam and the laser to evaluate them, including new electronics being developed by Louvain and Alberta. As shown below the proposal was extremely successful and has resulted in a validated detector concept and proposals by ATLAS and CMS to include such detectors in forward proton upgrades.

The Detectors. The fast timing detectors under development are shown in Fig. 1 and make use of prompt Cerenkov radiation and micro-channel plate photomultiplier tubes, MCP-PMT, combined with fast electronics to obtain unprecedented timing resolution.

Figure 1: (a) and (b) Conceptual drawings of a QUARTIC detector, showing the proton passing through eight fused silica bars of one row in x providing eight measurements of the proton time, and the 4×8 layout of QUARTIC bars, respectively; (c) a sketch of the GASTOF detector.

Micro-channel plate PMT's (MCP-PMT's) provide an alternative to standard dynode PMT's. Originally developed as amplification elements for image intensification devices, MCP's have direct sensitivity to energetic photons as well as charged particles and demonstrate a unique combination

of desirable properties including large gain, excellent spatial and temporal resolution, and the ability to operate in high magnetic fields. The superior time resolution of the MCP-PMT makes it a central element in a precision time-of-flight detector that is a critical part of a proposed ATLAS Forward Proton (AFP) upgrade project which will be implemented at the Large Hadron Collider (LHC) if approved. This new proton detector system enables a rich Standard Model program and could contribute to the measurement of new physics, such as the quantum numbers and mass of the Higgs Boson.

Fermilab Test Beam. In 2007 we had two one week test beam periods at Fermilab using 120 GeV protons. The T958 test beam experiment was led by the PI Andrew Brandt and involved personnel from University of Texas, Arlington (UTA), Alberta, Louvain, and Fermilab. These test beams resulted in a validation of the detector concept for GASTOF and led to a redesign of the QUARTIC detector.

The test beam setup included trigger scintillators bracketing two single channel GASTOF detectors G1 and G2 and an eight row QUARTIC detector. G1 was an initial prototype using a 25 μm pore Burle 85011-501 MCP-PMT with 4 of the 64 6 mm $\times$ 6 mm pixels ganged together, while G2 was a second generation prototype using a single channel Hamamatsu R3809U-50 with 6 μm pores. The QUARTIC detector consisted of 8 15 mm $\times$ 6 mm $\times$ 6 mm fused silica bars, each connected by an aluminized air light guide to a 6 mm $\times$ 6 mm pixel of a prototype 10 μm pore Burle tube.

The signal for the MCP-PMT's was amplified using a GHz amplifier, passed through a constant fraction discriminator (CFD), and read out by a Phillips 7186 TDC. Several types of amplifiers were tested: ORTEC 9306, Phillips BGA2712, Hamamatsu C5594, and Mini-Circuits ZX60-14012L. Several different CFD's were also used: ORTEC 934, ORTEC 9307, and a Louvain-made CFD circuit. We used a CAMAC based data acquisition system triggered by scintillator tiles located on either end of the detector setup. Multiwire proportional chambers provided track position information.

While the data acquisition system provided a wealth of data allowing us to compare the performance of the different components and multiple channels, the most useful results actually came from an analysis of waveforms recorded from four channels (G1, G2, Q1 and Q4) using a Tektronix DPO70404 4 GHz digital oscilloscope. Off-line we applied in software fixed threshold discrimina-

tion and constant fraction discrimination algorithms. From the time differences between all pairs of channels we infer the individual resolutions. With an optimized CFD algorithm we achieved $\delta t(G1 - G2) = 35 \pm 1$ ps (rms) as shown in Fig. 2; from all combinations we inferred $\delta t(G1) = 32$ ps and $\delta t(G2) = 13$ ps. The G2 detector was expected to be superior due to a better mirror and an MCP-PMT with better resolution. Unfolding the resolutions of QUARTIC bars, we obtained $\delta t \approx 60$ ps. The G1 efficiency was measured to be very high $\sim 98\%$, while the G2 efficiency was about 80% likely due to improper alignment of the spherical mirror (addressed in the next prototype). QUARTIC bar efficiencies were about 80%. The overall performance of the QUARTIC bars including electronics improved from 110 ps/bar in the initial 2006 run to 82 ps/bar in 2007, due to improvements in the CFD and the new PMT.

Figure 2: The time difference between the old (G1) and new (G2) GASTOF detectors.

CERN Test Beam. Following the 2007 Fermilab test beams we continued simulations to improve the QUARTIC detector. These demonstrated that although the short bars (15 mm) provided a narrow time distribution, longer bars (90 mm), despite having a wider time distribution due to color dispersion effects, might provide better results since they resulted in about twice the number of photons reaching the PMT (due to the superior efficiency of total internal reflection as compared to reflection off the aluminum light guide). Without a good model of how the MCP-PMT responds to photons that arrive at different times, it was not possible to use simulation to choose

Figure 3: The time difference between two 90 mm long QUARTIC bars as described in text.

between the two configurations, so we built a new prototype detector with four short bars and four long bars.

The goals of the fall 2007 CERN test beam were to study the efficiency of the detectors using a silicon tracking system and to measure the performance of a new QUARTIC prototype and a new constant fraction discriminator. This test beam was not successful, due to problems with the synchronization of the tracking telescope, and noise issues with the amplifiers, necessitating a second run, in summer 2008, which was extremely successful. Figure 3 shows the time difference between two 90 mm long QUARTIC bars from the 2008 CERN test beam run, with $\delta t(Q1 - Q2) = 56$ ps (rms). The signals from the Burle MCP-PMT were passed through the Louvain constant fraction discriminator (CFD), and the resulting NIM pulses were recorded with the LeCroy 8620A oscilloscope obtained with ADR funds. This result implies a QUARTIC bar resolution of 40 ps including the MCP-PMT and the CFD. Figure 4(a) shows the position distribution of tracks in a silicon strip detector (b) shows the subset of those tracks giving a valid time in one of the bars (c) the ratio of (b) to (a) demonstrates that the efficiency is $> 95\%$ across the bar. Given the high efficiency with two 8-bar QUARTIC detectors we expect an overall resolution close to 10 ps.

Electronics. In conjunction with colleagues from Louvain and Alberta we have developed and tested the full readout chain for the QUARTIC detector as shown in Fig. 5. The resolution of the electronics chain is less than 20 ps/channel, so the channel resolution of about 40 ps is dominated

Figure 4: (a) x-y distributions of test beam tracks in silicon strip detector; semi-circle shape is due to coincidence of trigger scintillator paddles vetoed by a scintillation counter with 15 mm diameter hole (single track events pass through hole and are not vetoed) (b) x-y distribution of events with a specific QUARTIC bar “on” (voltage above threshold) (c) efficiency versus position, determined by the ratio of tracks with the bar on divided by all events: plot (b) divided by plot (a).

Figure 5: The electronics chain for QUARTIC: the signal from the MCP-PMT is amplified by a high bandwidth low noise amplifier, such as the 3 GHz MiniCircuits ZX60, then converted to square pulse with the leading edge representing the time by a Louvain constant fraction discriminator, and finally digitized and sent to the ATLAS readout using the Alberta TDC featuring the CERN-developed HPTDC chip.

by the detector/MCP-PMT combination.

Picosecond Test Facility. In addition to simulation and test beam, we also employed a fast laser to design and evaluate all the components of the timing system except for the radiator. ADR funds allowed us to establish the UTA Picosecond Test Facility (PTF) in the Chemistry and Physics Building. The main components of the PTF are a light-tight box containing a Hamamatsu PLP-10 pulsed picosecond laser, with 405 and 635 nm laser diode heads, various associated optical equipment (lenses, mirrors, beam splitters, and filters), electronics (high voltage, discriminators, etc.), high bandwidth SMA cables and connectors, and a LeCroy 6 GHz Wavemaster 8620A oscilloscope.

Figure 6(a) shows the layout of the laser setup, which is capable of operating in (b) “beam mode” with two or three 5 mm diameter beams incident on different pixels of the MCP-PMT (the Burle/Photonis Planacon is shown in the picture) or (c), (d) “fiber mode,” which allows the simultaneous testing of up to eight different channels using a clear fiber bundle to distribute the laser light.

The PLP-10 laser has a variable frequency from 1 Hz to 100 MHz. Neutral density filters are used to control the amount of light incident on the tube allowing us to select predominantly single photoelectron events by filtering heavily (such that less than 10% of events have an output pulse, effectively isolating single photoelectron events), or events with hundreds of photoelectrons by reducing the filter strength. We have performed many measurements to demonstrate the effectiveness of our laser setup including measuring the single photoelectron timing response (transit time spread)

Figure 6: (a) Labeled photograph of typical laser setup. (b) Laser light incident on the PMT when operating in “beam mode” with a 5 mm diameter beam split into two approximately equal intensity sub-beams. (c) One of the laser beams split into eight clear fibers in order to strobe multiple channels of the MCP-PMT. (d) “Fiber mode” operation, with eight channels in one row being studied.

as shown in Fig. 7. Our measurement is in complete agreement with previous measurements of the Planacon by Jerry Va’vra of SLAC and others, with the tail to high transit time resulting from photoelectrons that “bounce” before being accepted by a pore. This recoil photoelectron effect can be reduced by decreasing the distance between the photocathode and MCP, and Photonis has made a version of the Planacon with a “dropped faceplate” that has a much smaller tail. In Fig. 8, we show that the timing is independent of gain at 10 photoelectrons, the approximate yield of a quartz bar. This shows that we can operate at low gain (5×10^4), which is essential for both rate and lifetime considerations (higher gain implies that the tube will saturate at a lower rate and that the PMT will be damaged more quickly than for lower gain).

Conclusions. This ADR proposal was extremely successful, culminating in the development of a 10 ps resolution time-of-flight system. The laser facility established with this grant has proven to be an effective tool for evaluating phototube and electronics performance as well as being an excellent teaching tool, allowing many undergraduate students to participate in forefront research.

Figure 7: Measurement of the single photoelectron timing for the 10 μm pore Planacon at the UTA Picosecond Test Facility (using a 405 nm PLP-10 laser).

Figure 8: Measurement of timing resolution as a function of gain at the UTA Picosecond Test Facility (using a 405 nm PLP-10 laser).

Technology Transfer Activities:

Publications and Conference Presentations:

- “The FP420 R&D Project: Higgs and New Physics with Forward Protons at the LHC,” FP420 Collaboration, arXiv:0806.0302v2 [hep-ex]; J. Inst.: 2009_JINST_4_T10001 <http://www.iop.org/EJ/abstract/1748-0221/4/10/T10001>.
- “QUARTIC, a 10 picosecond Timing Detector,” A. Brandt *et al.*, to be submitted to J. INST.
- “Laser Measurement of the Photonis Planacon,” A. Brandt *et al.*, to be submitted to J. INST.
- “Forward Protons from the SPS to the LHC,” Andrew Brandt, Louvain Seminar, Belgium, March 31, 2008.
- “Forward Protons from the SPS to the LHC,” Andrew Brandt, Charles University Seminar, Czech Republic, May 12, 2008.
- “Fast Timing is Hard,” Andrew Brandt, AFP Meeting, SACLAY, France, May 20, 2008.
- “Fast Timing for ATLAS/CMS,” Andrew Brandt, SPS Users Meeting, CERN, June 26, 2008.
- “Test Beam Studies for FP420 Fast Timing,” Andrew Brandt, Picosecond Workshop, Lyon France, October 16, 2008.
- “Forward Proton Fast Timing,” Andrew Brandt, Manchester Forward Physics Workshop, UK, Dec. 6, 2008,
- “Forward Protons,” Andrew Brandt, Lancaster University Colloquium, UK, Dec. 8, 2008,
- “UTA Laser Tests,” Andrew Brandt, Picosecond Workshop, Argonne, IL, February 27, 2009.
- “ATLAS Forward Proton Fast Timing,” Andrew Brandt, Photonis-USA, Lancaster, PA, April 30, 2009.
- “ATLAS Forward Proton Fast Time of Flight Detectors,” Andrew Brandt, Workshop on Fast Cherenkov Detectors, Giessen, Germany, May 12, 2009.
- “ATLAS Forward Proton Fast Timing,” Andrew Brandt, Photek, Sussex, UK, June 16, 2009.

Web Page: <http://www-hep.uta.edu/~brandta/ATLAS/AFP/AFP.html>

Collaborations: This proposal led to new collaborations with Photek LTD., a leading company in MCP-PMT development, and Arradance Inc., a company working on improving MCP technology using Atomic Layer Deposition. Several joint funding proposals including NSF SBIR and STTR proposals have been submitted based on the results of the DOE ADR proposal.